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Procedia Materials Science 2 (2013) 34 – 42
Procedia Materials Science
www.elsevier.com/locate/procedia

Materials Science Engineering, Symposium B6 - Hybrid Structures

Methods for modelling and analysing process chains for supporting the development of new technologies.

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Abstract

The paper wants to illustrate a new approach for modelling and analysing innovative technological process chains aiming at the determination of cause-effect relations between material properties and manufacturing conditions concerning the required component quality. The intention is to assist the domain specific experts at their research and development of novel technologies. A supporting software tool is under development. Using the example of the process chain of the manufacturing of a hybrid yarn textile thermoplastic composite component the application of the approach and the test of the software tool was performed for the modelling of the process chain and for the analysing of a selected process step. Therefrom requirements were derived for the further development of the methods and the software tool.

Selection and peer-review under responsibility of Conference organizers (MSE-Symposium B6).

Keywords: manufacturing data management ; domain specific process chain modelling ; data driven process optimisation

1. Introduction

To develop academic principles and methods for the development and use of novel „Textile-reinforced composite components for function-integrating multi-material design in complex lightweight applications“ the German Research Foundation DFG established the Collaborative Research Centre (CRC) 639 at the Technische Universität Dresden [Hufenbach, 2006].

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Selection and peer-review under responsibility of Conference organizers (MSE-Symposium B6).
doi:10.1016/j.mspro.2013.02.005

Compared to other groups of materials the textile-reinforced composites have the most flexibility in adapting the material structure to the loads. Therefore, they are ideal for composite designs with the best material mix possible for meeting the complex requirements in the field of lightweight design. The development of technological procedures for efficiently producing novel textile-reinforced composite components is a key subject of the works of the CRC 639. In order to arouse interest of different industries from the beginning, the desired procedures are under the claim of a high reproducibility and line production capability. Developing both novel materials and the associated manufacturing processes at the same time means that initially there is no sufficient practical knowledge available about the involved technologies. But a comprehensive knowledge is necessary because the technologies, which are used along the process chain „from filament to component" have strong influences on the component's final properties. Therefore, methods are required to support the generation of a technological knowledge base and to support the analyses to identify unknown cause-effect relations over the entire process chain. These methods are under development of the CRC-subproject E2. They are aimed at assisting the domain specific experts at the determination of a specific setting of predefined component properties and ensuring the reproducible manufacturing of thermoplastic textile composite components. To support the application of these methods a comprehensive software tool set is under development.

The motivation, the method set and the software were described in detail earlier in [Großmann, 2010 and Weller, 2010] and will only be briefly discussed here. The main purpose of this paper is not to discuss a new technological process itself but how domain specific experts can be assisted by modelling and analysing techniques at researching and developing of a novel technological process (chain). For a start, a characteristic and delimited demonstration example was chosen to validate the methodological approach and to test the software application before the modelling and analysing techniques will be further applied to the entire process chain of the CRC 639. As demonstration example serves the manufacturing of the composite component „shock absorber dome" (described in [section 4]), which is made of hybrid yarn textile thermoplastics (HGTT).

2. Background of the methodological approach

The software-assisted modelling and analysing of technological relations aimed at the design of process chains for the manufacturing or assembling of a component or a product is the subject of the computer-aided process planning (CAPP) discipline. CAPP tools support the derivation of process plans from computer-aided design (CAD) data as well as adaptive planning, planning of options and repetitive planning [Jacobs, 2002 and Eversheim, 2002]. They provide features for structuring and particularising process chains, for connecting predefined technological process building blocks (e.g. STEP-NC [ISO 10303-238 (2007)]), for the selection and association of optimised technological parameters from knowledge databases and for assembly planning. They also provide interfaces for the transfer of the process plans to systems for enterprise resource planning (ERP). CAPP tools are commonly used in conjunction with databases which provide enterprise-specific manufacturing know how, timetables, machine and material data. In general the assistance for process planning in terms of replanning, optimisation of planning or generic planning [Jacobs, 2002 and Eversheim, 2002] is not in the focus of CAPP tools because the tools for replanning are rather specific designed to fit the requirements of particular manufacturing procedures, groups of workpieces and materials. Furthermore the tools usually address only one or two operating ranges of the state changes during the technological process [Großmann, 2007]. The technological cause-effect relations inside the CRC 639 process chain are characterised by the complex interactions of various operating ranges and the application of the model is aimed at the optimised adjustment of the process parameters as well as the properties of materials, manufacturing equipment and final components. Therefore the well-known methods are only limited applicable for the description of such a process chain. The well-known methods for the production planning are usually focused on the delimited scope of a single manufacturing technique, e.g. at the metal forming the geometric state changes during the process are analysed by use of the finite element method (FEM). [Roll, 2006] addresses the consideration of material changes and [Brecher, 2009] addresses the consideration of environmental influences of machine and process. [Hirt, 2006] addresses the consideration of the process history of upstream process steps, e.g. the microstructure characteristics from the rolling process is considered at the dimensioning of the pulling process. [Klocke, 2004] uses Virtual Process Engineering that integrates the FEM and a Virtual Reality system in the manufacturing process chain and considers the material history for an integrated process simulation. For the planning of the process chain of glass moulding [Schuh, 2007] uses an approach that combines a product model (workpiece properties) and a process model (technological capabilities) for the derivation of the process chain. Based on the comparison of defined product characteristics and matching patterns of process capabilities the process chain is derived by selecting process steps that are compatible with the product. [Kühnert, 2009 and Bernard, 2011] are focused on data mining in the production environment (industrial batch processes) with applications in the shop-floor-area and in the chemical industry.

The exemplary referred research works may show the efforts across different disciplines to unlock additional potentialities of the reproducible manufacturing under economical and qualitative evaluation criteria by having the process chain view in mind when considering a single process step. The referred approaches are rather technology-specific. General methods for modelling and analysing the complex technological process relations between the operating characteristics of the manufacturing equipment and the final component properties (not only for documentary-administrating application but also for planning and controlling application) which could be adapted directly to fit the needs of the CRC 639 were unknown at project start.

3. The methodological approach

The method set is mainly based on the following three core concepts, which take effect by performing several tasks around a central data model [Fig. 1]: (1) the systematic preparation of the technological experiments together with the domain specific experts, (2) the manufacturing-accompanying acquisition of the relevant experimental data (e.g. properties of semi-finished and final components, setting and disturbance variables) and (3) the analysing of the acquired data addressing various issues (e.g. determining suitable process windows, identifying relevant cause-effect relations inside the process).

3.1. Describing of the technological process and preparing of the experiments

The domain specific experts are usually not very familiar with this way of process description. Especially the appropriate use of the modelling language, the concept of object type classes, types and instances [Weller, 2010] and the distinction, which parameters should be considered and which not (e.g. invariants) are not easy in the first place.

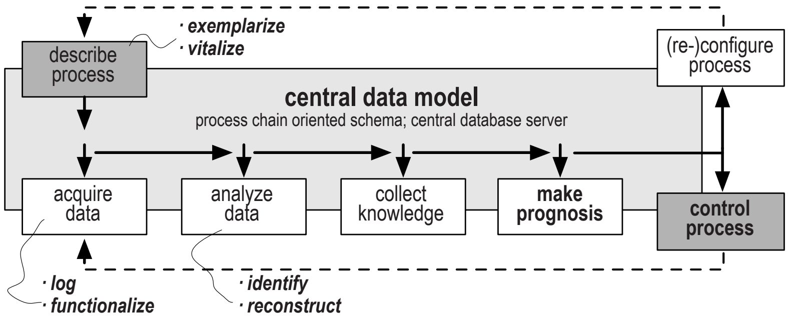

Fig. 1. The methodological round-trip

Therefore, a goal-oriented discussion with the domain specific experts about the initial technological situation, the process characteristics and the available experience is essential. By using special questioning techniques the assumptions and experiences can be easily collected for the use of the process modelling and can afterwards be systematically integrated in the research works of the domain specific experts. Further the technological objectives (e.g. required boundary conditions, final component properties) are specified and the experimental targets are defined (e.g. „determine a suitable process window“). As a result of these discussions the process (chain) is described by means of a graphical model [Fig. 2] [Hufenbach, 2011] based on the rules of the modelling language [Weller, 2010]. It contains the process participants (input and output materials, utilised resources) including their state parameters and their structural arrangement. This process model is not only a very handy communication tool for supporting the collaboration of the domain specific experts but it is also used to transparently configure the underlying database, which is configured automatically in the background [Großmann, 2010]. Therefore, this first task is an essential preparative step for the following functions of information handling. The process modelling software tool is implemented as a modern web application – a distributed client/server system that supports multi users on multi locations. Therefore, to use the tools the project operator only needs an Internet browser with network access, regardless of where he is located.

Based on the process description and depending on the objectives, the experiment can now be prepared. To achieve a meaningful and effective experiment scope, the planning is made by using methods of the „Design of Experiments“. At this point in the process, it is recommended that a projection is made to determine which methods of analysis should be applied on the experimental data, as these could affect the experimental design. In preparation of the manufacturing experiments, a data acquisition strategy needs to be specified. In addition to that, the software tool needs to be configured for supporting the chosen strategy, especially for the machine connections, input forms and import filters. They are needed to acquire the machine settings, the environmental or product-related measurements, the subjective ratings of component quality, and the observed exceptions during the process execution. An essential part of the experiment is the consistent component identification. This is necessary to associate the experimental data uniquely and properly with the component objects in the database. It is also necessary for a continuous tracing of the components along the process chain.

3.2. Acquiring of the relevant experimental data

During the experiment the actual properties of the component instances as well as the actual state-changes of the process instances and resource instances are logged and stored in the database. This can be done manually by input forms, semi-automatically by import-interfaces (e.g. for log files retrieved from machine control) or fully automatically by connection to a factory data capture system.

3.3. Analysing and synthesising of the acquired data

In the next step the acquired data passes a systematic error correction and is thereafter goal-oriented analysed and visualised. This means that various algorithms can be applied to complete the task. Currently, the software tool can directly perform standard analyses such as the computation of statistical variation of measurements over experimental series. For more complex analyses (e.g. identifying cause-effect relations between multiple process parameters), functions of the external analysis tool „R“ are integrated transparently in the web application. In addition to that, data export interfaces to other analysis tools (e.g. Microsoft Excel, MATLAB/Simulink) are available. The analysis results are presented understandably and will be interpreted and discussed together with the domain specific experts. If necessary, the acquired data will be analysed again considering further aspects. Based on the analysis results and the pre-existing knowledge mathematical models can be synthesised. With these models it is possible to make predictions on how specific process parameter settings can affect specific component properties. Therefore, they can be used for process control as well as for re-configuring of the process settings. At the end of the process, the mathematical models have to pass a final validation in the manufacturing system.

3.4. Collecting and utilising of the process knowledge

All the knowledge items, which were worked out through the modelling and the analyses will be systematically stored in a structured way to support effective reusability and thus form a process knowledge database. Knowledge items are the determined process windows (as manufacturing settings), the material parameters (as a basis for simulation applications), the models of cause-effect relations (as a basis for process control), and the process models as well (as a basis for process planning). Like the diversity of applications, the forms of presentation are also different: the process windows could be provided as technology tables and the process models as technology templates from a library of the modelling tool.

4. The application of the methods

As already mentioned the manufacturing process of the composite component „shock absorber dome“ was accompanied to validate the methodological approach and to test the software in terms of functionality, stability and usability. The component and the manufacturing environment were developed in the research project „EFFEKT“ (Near-Net-efficient manufacturing processes for thermoplastic composites) [Großmann, 2011]. The „shock absorber dome“ is a structural part of the generic CRC 639 technology demonstrator „function-integrating vehicle system unit“ (FiF) and serves as housing for the shock absorber at the chassis. The final components of the FiF are made of multi-layered knitted-fabric composites. However, because of financial reasons the technological experiments described here used commercial fabric. [Fig. 2] presents the graphical model of the „shock absorber dome“ process chain which consists of the following four process steps: „Preforming“ on Hexapod (including plasma cutting, stacking, and ultrasonic-stapling) [Machova, 2011], „Transport“ from Hexapod station to the Press station, „Consolidating“ by hot pressing [Borriboon, 2011] and „Post-processing“ (edge cutting and quality assurance) [Geller, 2011].

4.1. The objectives of the technological experiments

In the first place, an appropriate parameter area had to be determined for the required component properties. As a result, the following quality goals were specified for optimisation: compound thickness, the maximal bending stiffness as well as the avoidance of fibre damage.

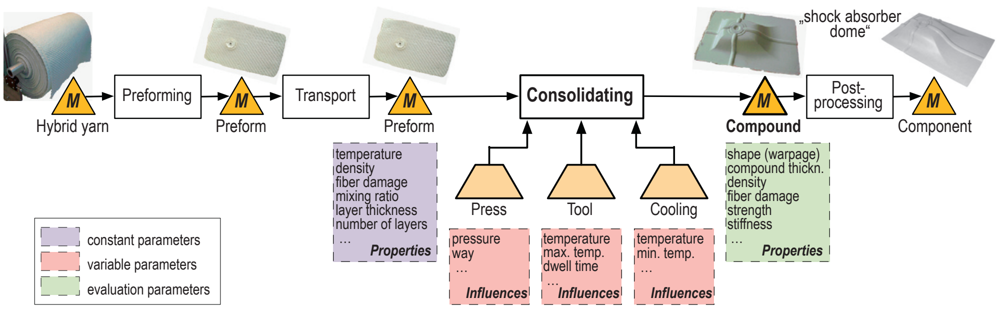

Fig. 2. Graphical model of the demonstrator process chain

Additionally, these quality goals should be achieved with minimal energy input since the „Consolidating“ process is very energy consuming. Furthermore it is necessary to identify cause-effect relations between the setting and disturbance process parameters and the final component properties. Those can be used to improve the stability of process execution as well as the structural design of the product. The process reproducibility is an essential requirement for a subsequent line production. Therefore, the determined process parameter windows have to be validated by further experimental series.

4.2. Experimental data acquisition

In consequence of the complex relations inside the process chain and the limited manufacturing capacities the methodological validation and the software test focused on the „Consolidating“ process step. As a prerequisite for such an isolated view it was necessary to ensure mostly constant input parameters. This was targeted by several actions. On the one hand, only commercial Twintex T PP (35% glass) fabric of one batch was processed to minimise fluctuations in the input material. On the other hand, no parameter variations in the „Preforming“ process were made. To reduce any possible remaining fluctuations of the preform properties to a minimum, the preforms were checked and defective ones were sorted out. The acquisition and the analysis of the experimental data cannot be considered separately. The particularly applied analysis algorithms usually have an impact on the experimental design. Therefore, the experimental design has to be adapted with specific acquisition actions to meet the specific requirements of the chosen algorithms. This affects not only the influences and properties to be acquired but also the procedures of the component inspection. The inspection conditions have to be considered, as they are essential to the measurement tolerances.

The experimental program consisted of ca. 200 production cycles and included the variation of the following process parameters: temperature of pressing, temperature of extraction, pressure under press temperature and dwell time under press temperature. Some pre-passes were performed to determine useful variation zones. Then a full factorial experimental plan followed with 5*6*3 stages and 2-time replication. After those main passes and the following analyses (described in [section 3.3]), some extra passes were performed to validate the results regarding reproducibility. To realise a continuous identification system every instance object received a unique identifier (ID). Barcode labels and handwritten numbers were used, but RFID chips are also possible. In conjunction with the software function „instance object history“, the required traceability along the entire process chain for every instance object was ensured.

The data acquisition was done manually by input forms as well as automatically by a connected factory data capture system. Some properties such as the fibre damage could only be determined qualitatively. Therefore, a concept was developed for recording and rating visual inspections. As part of this it is possible to rate a criterion using predicates (e.g. „very good“, „good“, „satisfactory“, „inadequate“). [Table 1] lists selected process parameter data, which were acquired during the execution of the experiments and the subsequent inspections of the manufactured components.

Table 1. Selection of acquired process parameters

Goods inward	Preforming and Transport	Consolidating and Post-processing	Component inspection
composite fabric (Twintex) properties according to manufacturer information	layer structure, patterns and parameters for cutting and tacking, fibre damage, observed special events	set/actual tool temperature, coolant temperature, pressure and dwell time, fabrication particularities	geometric variables (e.g. shape/ warpage, compound thickness), surface texture, colour, fibre damage, deflexion under load

4.3. Experimental data analysis

At the beginning of the data analysis, the data was passed through a completeness and correctness screening. Wherever possible and necessary, the detected errors were corrected. As the screening revealed, the records of the first days of the experiment were not fully completed. This may have been due to the operator's lack of experience. Furthermore, the sensors for capturing the energy consumption were not installed from the beginning, so they could not be used in the first passes. In addition to this, there were some typos such as decimal points instead of commas or implausible numbers (comma error). By questioning the operators these input errors could be corrected.

The target of the first analysis task was to determine a process window for manufacturing with a maximum bending stiffness in accordance with the permissible component thickness. Therefore, mathematical models were developed using statistical methods (multiple linear regression, non-linear regression, support vector machines) to reflect the behaviour of the data and thus enable predictability. [Fig. 3a and 3b] show an example of how temperature and pressure influence the bending stiffness. The box plots show the influence of the process parameters in their entirety at different temperatures as well as the variation of the bending stiffness in the components as a result of the actual processes. A low variation is a good indicator for reproducibility.

A high level of process control and a target-oriented design of components and processes require the knowledge of how the technological process can be influenced with regard to a specific target figure. For this purpose, a sensitivity analysis was performed, which showed the relative strength of the influence of various parameters within their prescribed variability as well as the direction of this influence.

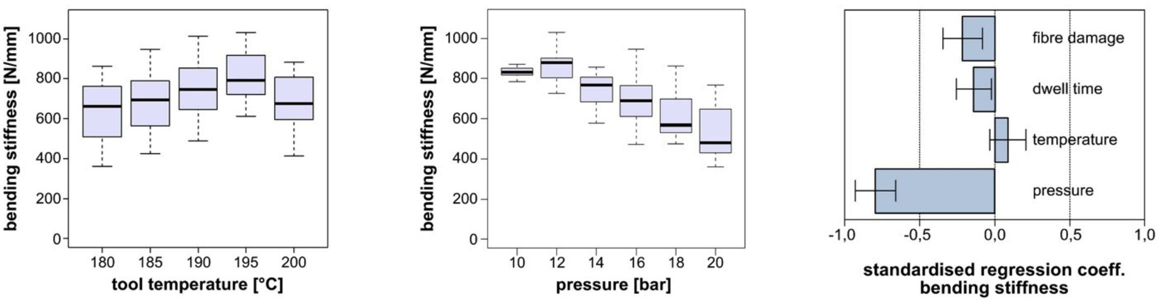

Fig. 3. Bending stiffness of the component (a) in relation to the tool temperature; (b) in relation to the pressure; (c) under a sensitivity analysis – relative influence of individual parameters

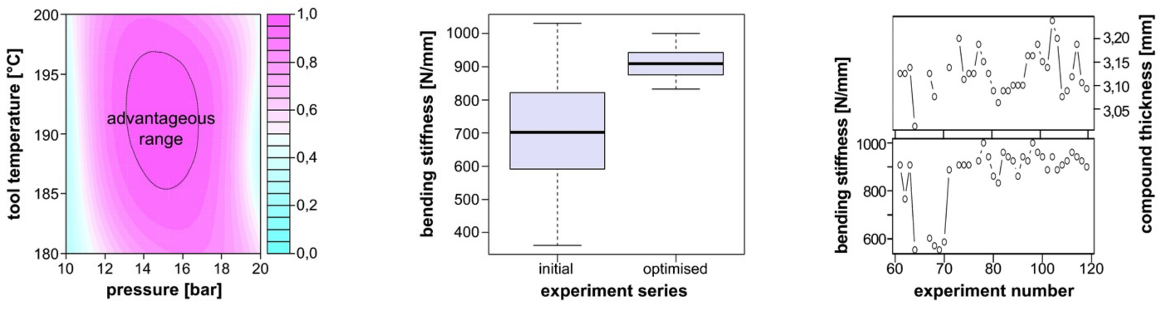

Fig. 4. (a) Determined process window for „Consolidating“ – optimised towards bending stiffness and compound thickness; (b) Bending stiffness results of the first series compared to the validation series; (c) Progression of bending stiffness and compound thickness during the validation series

There are different types of sensitivity analyses, whose results must be interpreted differently. [Fig. 3c] presents a rather basic type, the standardised regression coefficient, which shows the influence of various parameters on the bending stiffness. As seen, the parameter with the highest influence is the pressure followed by the fibre damage. For the design of a control strategy, the sensitivity analysis can be very helpful because it can guide from a raw setting to a finer parameter adjustment. [Fig. 4a] shows the predicted probability of success for producing a component, which meets the requirements at different settings. Within the thus determined process window a fixed set of parameters was chosen to perform another experimental series to validate the reproducibility. [Fig. 4b] brings the results of the first experimental series face to face with the results of the validation series. [Fig. 4c] shows the progression of compound thickness and bending stiffness over the progression of the experiments (validation series). After some initial difficulties a good reproducibility was achieved.

Some remarks on the presented analysis are necessary: The analysis results are primarily only valid for a single parameter (bending stiffness). To derive a control strategy for the adjustment of multiple target figures the used algorithms reaching their limits and more complex methods, such as the support vector machines and similar methods in conjunction with various optimisation strategies, are necessary. Therefore, specific analysis concepts need to be developed to cover these multi-parameter influences.

5. Conclusion and outlook

The prototypical development and the start-up of the process chain of the manufacturing of the „shock absorber dome“ was successfully accompanied and assisted by methods for modelling and analysing the process chain (e.g. at the experimental design and the determining of suitable process windows) and by the supporting software tool. Additional technological improvements are reasonable in the industrial application.

Due to the prototypical development status of the software tool, the acquisition of the experimental data was largely done manually. Thereby the „human factor“ has proved to be the most error prone part. Therefrom can be concluded to use automated data acquisition wherever possible and to simplify the tasks that still have to be done manually because they cannot be automated. Additional appropriate functions are necessary for validation of the inputs (e.g. plausibility checks). To enhance the software support for these manual tasks the following requirements can be derived:

- Clearly structured input forms for improving the concentration and for reducing the failure rate
- Small manageable work units by splitting of complex content (e.g. inspection point oriented step-by-step instructions)
- Graphical support for visual inspections (e.g. pictorial instructions)
- Completeness and error checking just during data input (e.g. adhoc partially analysis to detect exceptions)
- Mandatory (automatic) logging of modifications in the experimental design

The experiences during the data analysing can be summarised as follows: An in-depth understanding of mathematics is required to take advantage of the analysis algorithms. Such knowledge is usually not present at the domain specific experts. Even the choice of the „proper“ analysis algorithm is problematic, especially in the context of the experimental design. The provisioning of easy access to the analysis functionality is a major subject of further developments thus the power of the algorithms can be utilised goal-oriented by non-mathematicians. Another challenge is the clear and user-friendly visualisation of the analysis results, because the results have to be evaluated and discussed by several experts of different scopes, which usually have different perspectives (e.g. economical vs. energetical view).

The objective of the reported project stage was the validation of the methodological approach. All together, the methods developed in the CRC 639 subproject E2 could be applied successfully to a selected and delimited demonstration example of a novel (process chain based) technology. The greatest benefit potential of the application lies in the effective and process oriented data analysis. Nevertheless there are further development needs as aforementioned. The next step will be the application along the entire CRC 639 process chain – the results will be reported.

Acknowledgements

The works presented in this paper are funded by the German Research Foundation DFG (Deutsche Forschungsgemeinschaft) within the Collaborative Research Centre (CRC) 639 „Textile-reinforced composite components for function-integrating multi-material design in complex lightweight applications".

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